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Generation IV Roadmap

Crosscutting Economics R&D Scope Report

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EXECUTIVE SUMMARY

This report has been prepared by the Generation IV Economics Crosscut Group (ECG) as part of the Generation IV Roadmap program to identify generic issues that require R&D to achieve the economic goals of Generation IV nuclear energy systems. The Department of Energy recognizes that the Generation IV Technical Working Groups (TWG) could employ several common technologies in many reactor systems now being proposed. Therefore, opportunities may exist for more than one system to benefit from a particular R&D effort. Thus, the Roadmap process has established R&D Crosscut Groups (CG) to explore these generic opportunities: Fuel Cycle (FCCG), Fuels and Materials (FMCG), Risk and Safety (RSCG), Economics (ECG), and Energy Products (EPCG). This report focuses on the generic economic issues that should be addressed regardless of the Generation IV concepts to be developed and deployed.

Generation IV nuclear energy systems should be suitable for widespread application in developed and developing countries alike, and meet broadly defined goals of sustainability, economics, safety and reliability, and physical protection and proliferation resistance. The economic goals of Generation IV nuclear energy systems, as adopted by Generation IV International Forum (GIF), are to have a life cycle cost advantage over other energy sources, and have a level of financial risk comparable to other energy projects.

The ECG expects this report to stimulate discussion and critical thinking on economic issues related to new nuclear energy systems and their associated fuel cycles that could, in the long term, offer substantial advances and breakthroughs. The present report is structured according to key economic issues and challenges identified during this phase of the Roadmap program. It draws from material provided by the ECG and proposals included in R&D scope reports from TWGs.

In Section 2 we review and propose methods for cost reduction, with capital cost and associated factors being the dominant cost drivers. Section 3 recommends that a broader view of energy products beyond electricity be considered and identifies the key issues that must be resolved. Section 4 reviews current models and proposes the development of an overall economic model for use in Generation IV activities. Section 5 discusses the broader issue of R&D deployment, with a proposed evolutionary process for R&D deployment and funding. This, combined with joint energy products considerations, is critical for Generation IV success. Section 6 summarizes the ECG recommendations for generic economic R&D activities. Bibliographic references and associated appendices at the end of the report provide source books and documents supporting the methodologies and approaches proposed.

The ECG believes that the following issues are of critical importance in the process and development of Generation IV technologies:

- A decision-making process should be developed to identify how research and development costs should be deployed for maximum advantage to all GIF countries using viability criteria as a basis for investments. In this connection, the potential benefits of R&D programs on crosscutting issues and enabling technologies should not be overlooked. The process should help determine how to invest limited resources in all the Generation IV systems in the critical viability areas and when to move resources from one system to another that is more viable.

- To be in a position to determine the economic viability of the Generation IV nuclear energy systems, a standardized robust cost estimating protocol needs to be developed to provide decision makers with a credible basis to assess and eventually select future systems taking uncertainties into account.

- All R&D programs on each Generation IV system should include generic work to identify cost reduction strategies that will be necessary for a competitive nuclear option, taking into account the needed risk premium on the rate of return resulting from the long payback period on nuclear energy systems.

- Since many technologies are planning to utilize process heat applications or actinide management in their energy deployment strategy, a consistent method of treating the capital, operating, and revenue allocations will be necessary to credit these applications fairly.

- It is important to understand the fuel cycle cost implications of any system that has strong advantages in sustainability. For example, how should an accounting scheme recognize long-term sustainability advantages (e.g., of reprocessing) if it is not economic.

- The cost of licensing Generation IV plants that will be new to the regulator must be factored into economic analyses. Developing the licensing framework and standards for Generation IV technologies should be integrated in the R&D program to ensure that cost of licensing a plant during its deployment will be low and predictable enough not to deter investors from proceeding with Generation IV systems.

- Although beyond the scope of the Roadmap, the cost of demonstration plants likely to be needed for Generation IV systems should be included in the cost of development. Also, deployment costs, such as First-of-a-Kind engineering, while not included in the Roadmap, should be identified to make informed technology selections.

Crosscutting Economics R&D Scope Report

1. INTRODUCTION

This report has been prepared by the Generation IV Economics Crosscut Group (ECG) as part of the Generation IV Roadmap program to identify and discuss generic economic issues that deserve research and development (R&D) to achieve the economic goals of Generation IV nuclear energy systems. This R&D scope report focuses on generic crosscutting economic issues that must be addressed for all the Generation IV nuclear reactor systems that will be developed and deployed.

With the participation of the Generation IV International Forum (GIF), the U.S. Department of Energy (DOE) initiated work on the Generation IV nuclear energy systems technology Roadmap. The Roadmap activity is designed to:

- Articulate a vision of nuclear energy in the future (2030 and beyond)
- Establish a set of goals for nuclear energy systems that support the vision
- Evaluate nuclear energy systems currently at various stages of research and development in relation to these goals
- Identify the R&D advances needed to achieve the stated goals in the context of regulatory and institutional constraints.

The Roadmap process is expected to stimulate innovative and critical thinking on new nuclear energy systems that could offer substantial long-run advances.

DOE and GIF recognize that the Technical Working Groups (TWGs) could employ several common technologies in many of the reactor systems under consideration. Therefore, opportunities may exist for more than one system to benefit from a particular R&D effort. As a result of the Roadmap process, R&D crosscut groups (CGs) were established to explore the following generic opportunities: Fuel Cycle (FCCG), Fuels and Materials (FMCG), Risk and Safety (RSCG), Economics (ECG), and Energy Products (EPCG).

Generation IV nuclear energy systems should be suitable for widespread application in developed and developing countries alike, and meet broadly defined goals of sustainability, economics, safety and reliability, and proliferation resistance and physical protection. The economic goals of Generation IV nuclear energy systems, as adopted by GIF, are to have a life cycle cost advantage over other energy sources, and have a level of financial risk comparable to other energy projects.

For each goal, the Evaluation Methodologies Group (EMG) developed criteria and metrics to be used by the reactor-system-based TWGs to evaluate the potential of the various systems considered. Five criteria have been used to assess Generation IV systems against the economic goals: (1) overnight capital cost, (2) production costs, (3) construction duration, (4) capital at risk, and (5) average cost, where criteria (4) and (5) are calculated from the first three. Each of these criteria is addressed in Section 2.

The present report is structured according to key economic issues and challenges for research teams and policy makers identified during the screening phase of the Roadmap program. It draws from materials provided by ECG members and proposals included in R&D scope reports from TWGs. Crosscutting R&D economic issues for inclusion in the GIF R&D program (see Table 3) are intended to complement system-specific R&D programs and other crosscutting programs. The issues identified as deserving R&D cover the viability and performance phase requirements.

Section 2 covers major generic topics identified by the ECG and TWGs as candidates for crosscutting economic R&D programs. Section 3 introduces issues raised by an economic assessment of electricity and other energy products in the context of future, likely deregulated, markets. Section 4 focuses on economic modeling and proposes R&D aimed at the development of enhanced tools for economic assessment of Generation IV systems. Section 5 discusses the broader question of R&D deployment, with a supporting appendix (Appendix A) that offers examples of how to manage and evaluate the progress and outcomes of R&D projects within the follow-up phase of the Generation IV Roadmap program. Section 6 summarizes the generic economic R&D activities that should be considered. Bibliographic references at the end of the report provide documents supporting the methodologies and approaches proposed.

2. CROSSCUTTING R&D FOR COST REDUCTION

Recognizing that economic competitiveness is a prerequisite for a new nuclear unit to be considered as a candidate by utilities and investors, high priority should be given to identifying technologies and processes that reduce nuclear unit cost, while maintaining a high level of safety. Accordingly, defining and implementing the R&D programs necessary to deploy these cost-reduction-related technologies and processes are a key part of the Generation IV Roadmap. Methodologies and computer tools that assess the cost of innovative nuclear reactor designs and could assist R&D teams and the GIF in designing programs, policies, and priorities are addressed in Section 4.

Topics that could be addressed by generic, crosscutting economics R&D include:

- Capital cost and financial risk reduction (lower overnight costs and shorter construction time, lower capital at risk during construction, and lower decommissioning costs)
- Operations and maintenance (O&M) cost reduction
- Waste management and disposal cost reduction
- Improved overall lifetime efficiency (including production of co- or by-products).

The ECG recommends that an effort be made during the viability phase to investigate those issues in the context of crosscutting R&D programs in support of several Generation IV systems.

Fuel cost, representing about 20% of levelised generation cost in current nuclear power plants (less for reactors fueled with natural uranium), deserves attention. However, it is expected (1) that the FCCG will generate proposals in the field of overall fuel cycle efficiency, and (2) that the FMCG will generate proposals in the field of fuel performance enhancement that should address cost reduction issues.

2.1 R&D for Capital Cost Reduction

Since capital costs, including Interest During Construction (IDC), account for about 60% of the levelised electricity generation cost in current nuclear power plants, reducing these costs is especially relevant for the success of future concepts (see IAEA, 2002). Some obvious means of reducing capital costs (e.g., design streamlining and simplification) are likely to be reflected in Generation IV systems. Improvements will require research to develop new approaches and methods or to adapt existing methods from other industries.

2.1.1 Overnight Capital Cost

Many approaches that are being explored for reducing construction costs deserve further R&D efforts. Most Generation IV concepts selected would benefit from generic R&D in the field of advanced engineering methods; enhanced computer-aided design techniques; new approaches to meet safety goals; and improved fabrication methods (including modularization and prefabrication; streamlining documentation; and integrating design, equipment procurement, and construction progress reporting).

Reduction of “nuclear certified” materials and components in a nuclear power plant could lead to significant cost reduction. This requires a systematic review of necessary materials and equipment, comparing nuclear grade with the quality and reliability of available commercial grade materials and equipment from suppliers serving other industries. The experience of other industrial sectors such as aerospace and automobile could provide some insights in this field. The generic crosscutting R&D

proposed will focus on the approach to a comprehensive listing of requirements and a systematic comparison with materials and equipment readily available.

Further insights and practical experience regarding the shrinking of the nuclear safety grade envelope could be obtained from tracking the implementation of the Risk-Informed Regulations process in advanced nuclear plant licensing reviews. In the area of safety, a move toward more risk-informed and performance-based regulations, and flexibility in meeting regulatory requirements, are elements for restoring the competitiveness of nuclear energy. Generic studies, including cost-benefit analysis, could be carried-out to assess the importance of these regulatory changes on the detailed design of Generation IV concepts and their eventual cost. A comprehensive assessment of passive safety systems and their cost effectiveness could also be useful. However, we expect that the RSCG will propose crosscutting R&D in this field.

For current generation reactors, the non-nuclear part of a nuclear power plant represents roughly the same share of overnight capital cost as the nuclear island. In terms of overall efficiency, it would be relevant to investigate the needed R&D on the non-nuclear part (e.g., turbine, electrical, and other equipment) of the plant to ensure competitiveness. For instance, the impacts of increased computerization and cable multiplexing on the electrical building should be evaluated. While some aspects will be concept-specific (and even site-specific), crosscutting R&D could address generic issues and provide guidance applicable to all Generation IV systems undergoing viability assessment.

2.1.2 Licensing Standardization

The current licensing procedures are country-specific. This leads to large additional licensing costs each time a nuclear power plant of a given type and design is built in a new country. Also, and more relevant at the viability assessment stage of Generation IV systems, country-specific licensing procedures induce country-specific design characteristics. The establishment by GIF countries of commonly agreed guidelines on licensing practices would result in a major step forward in the economics of Generation IV systems.

A crosscutting R&D program aimed at establishing harmonized licensing procedures within GIF countries could start by identifying similarities and differences in licensing requirements of those countries. Information exchange across countries and between regulators and R&D teams would provide opportunities for analyzing the rationale for different approaches and identifying methods for building on common features.

2.1.3 Construction Duration

Construction time has a direct impact on capital cost through some of the indirect cost components, such as site engineering and supervision (see Table 4.1, Account 93) and through IDC. Also, construction duration has an indirect impact on financial risk and profitability by delaying the commissioning of the plant. Construction duration has a major impact on the perception of project risk, and hence on the premium charged through the cost of capital on the investment. Furthermore, construction duration risks may affect the economic performance of reactor suppliers. The potential reduction of risky, long lead-time capital projects is one of the most important criteria in deciding whether to commit to a new project.

Methods for reducing construction time involve generic issues that could be explored for the benefit of all systems, such as use of computerized project management techniques, open top construction methods, and slip-forming techniques. It is proposed to take advantage of experience through a review of approaches adopted for nuclear power plants built recently and proposed for evolutionary advanced reactors. This background research will serve as a starting point for identifying key issues to be addressed by future R&D programs within Generation IV.

2.1.4 Decommissioning Cost Reduction

Although the share of decommissioning in the average levelised cost of nuclear electricity generation is small, the absolute value of decommissioning cost is high and could be lowered. Dismantling, decontamination, waste management, and site restoration techniques are generic by nature and R&D programs in this field would benefit all Generation IV systems. Feedback from experience in decommissioning research and commercial nuclear facilities should be analyzed. The R&D programs should identify early on how best to design and construct plants to minimize decommissioning costs.

2.2 R&D for O&M Cost Reduction

O&M costs represent about 20% of the nuclear electricity generation cost and, once the plant is built, improvement of marginal costs (O&M and fuel) is the only avenue available to face the challenge of price uncertainties in deregulated markets. Low and stable marginal costs are a key element for the economic viability of Generation IV systems. Generic R&D issues in this field may be difficult to identify as long as Generation IV systems have not reached detailed design level. However, a number of topics could be investigated for the benefit of all systems.

Design simplification aimed at easier access by operation and maintenance workers and generic R&D on material resistance to irradiation and thermal degradation are among the possible crosscutting topics for generic R&D applicable to all concepts. Manpower training techniques should be investigated and assessed for efficiency, and R&D programs should focus on design and implementation of generic training equipment and organization (see IAEA 1999).

“Smart” equipment and predictive maintenance technology can reduce maintenance costs and improve safety and reliability. To facilitate the introduction of such technologies in Generation IV reactors, optimization analyses will be necessary for each concept. However, generic methodologies should be developed to:

- Assess how the reliability of equipment could be improved by the addition of smart monitoring and diagnostic features
- Explore the integration of data provided by smart equipment in the management of plant O&M (see results of relevant National Energy Research Institute (NERI) projects)
- Define the optimal staffing level of an advanced and modern new plant
- Determine the staffing levels required in a small modular plant, and the possibility of staff sharing among similar modules in a plant, leading to overall staffing reduction.

2.3 R&D for Waste Management and Disposal Cost Reduction

While the back end represents no more than a quarter of total fuel cycle cost, reducing waste management and disposal cost is important to alleviate financial risks and enhance public acceptance. As long as solutions for the disposal of all radioactive waste are not implemented, uncertainties in this field have an impact on public perception and acceptance of nuclear energy systems. It is assumed that R&D aimed at minimizing the volume and radioactivity/radiotoxicity of waste will be covered by the FCCG. From an economic viewpoint, specific R&D programs could be focused on reducing costs of conditioning, storing, transporting, and disposing of radioactive waste. The experience with interim storage, waste treatment, and, in some countries, final disposal should be reviewed to identify major cost components and key issues deserving more research.

2.4 R&D for Improved Overall Lifetime Efficiency

Lifetime extension, higher availability, and the production of by-products increase the technical efficiency (total energy equivalent per unit of input fuel and per unit capital cost) and can increase greatly the profitability of nuclear power plants. Most methods to improve these factors are generic and applicable to a wide range of concepts.

Increasing the efficiency of electric energy production is one important objective for cost reduction. At the beginning of the development of present-generation light water reactors, the thermal efficiency of the nuclear power plants were similar to the efficiency of the fossil-fuel plants. Fossil-fuel plants can profit from the development of high-efficiency combined-cycle gas or high-efficiency supercritical steam cycles.

The nuclear power plants of the new generation must address the technological improvements that have been incorporated into fossil-fuel plants. Generic enabling technologies that could be considered to enhance economic performance of Generation IV systems include:

- Direct cycle for gas-cooled reactors
- Supercritical steam cycles for water-cooled reactors
- Supercritical steam cycles and/or steam re-superheating in the steam generators for liquid metal-cooled reactors
- Supercritical CO_2 Brayton Cycle for liquid metal-cooled reactors.

Generic R&D topics relevant to facilitate lifetime extension (and reduce the cost of necessary refurbishment for extending the design lifetime of Generation IV concepts) include evaluation of aging and degradation mechanisms (irradiation, corrosion, fatigue), assessment of preventive and corrective maintenance efficiency, and enhancement of monitoring, surveillance and inspection techniques.

Design improvements and production strategies to increase availability factors are likely to be addressed through safety and reliability R&D (to be investigated by RSCG), as well as maintenance efficiency improvement (addressed above under O&M cost reduction). Generic R&D on cost-effective production of hydrogen and water desalination with nuclear energy would benefit most Generation IV concepts. Although we address some of the economic issues in the next section, the Energy Product Crosscut Group (EPCG) report will address the production of by-products such as heat, hydrogen, and potable water.

3. COST OF ELECTRICITY AND OTHER ENERGY PRODUCTS

3.1 Background

Generation IV nuclear energy systems are expected to be demonstrated by 2030 and commercially deployed through the second half of the 21st century. Assessing the economic performance of those systems is a challenge because of the large uncertainties on the precise characteristics of Generation IV systems, once developed, as well as in the long-term context, e.g., economics of alternatives. Some key issues to be addressed in connection to this are discussed below to highlight driving factors for enhancing the economic performance of Generation IV systems, as an introduction to the R&D programs proposed in the following sections.

3.2 Electricity Cost Issues

Historically, the primary function of a utility company has been to provide electric service for its customers. This implies that it produces electricity with some technological system, usually with a particular fuel source, as well as builds and maintains the electrical transmission and distribution systems, and customer service system. This structure of the electric utility industry has been in a state of flux over the last few years. For example, in the northern Midwest of the United States, utility companies are linked with independent power producers (IPPs). These IPPs have built or have purchased electrical generation power plants (primarily gas and coal). They produce electricity and sell it to customers at the spot-market price (i.e., excluding transmission and distribution costs). In many cases, the generation costs for old fully amortized plants are basically identical to production costs. Thus, the economics of the plant (capital improvement costs and production fuel-operation costs) may be separated from the economics of the electrical distribution system and customer service under some circumstances.

The revenue that the utility or the IPP receives from its customers for producing the electricity must balance the costs of the business and provide a rate of return for their equity investors (stocks) and to pay their debtors (bonds). The following economic discussion is based on the engineering-economics planning approach. We consider the situation of planning for the building and operating a power plant to produce electricity (and possible joint energy products), which is applicable to a utility or an IPP. These principles are general, but are applied to nuclear energy systems, and with slight modifications can be applied to any part of the power production business or to other parts of the nuclear fuel cycle.

3.3 Multiple Product Cost Issues

When a firm is selling multiple products in multiple markets, the allocation of fixed costs among the products is no longer straightforward. The allocation of fixed costs among multiple products should be addressed before the economic evaluation at the end of the viability phase of the Generation IV Roadmap.

Generation IV nuclear energy systems could produce two or three products, including electricity, domestic and/or process heat, potable water, hydrogen, and actinide management services. Depending on local context and market conditions, nuclear energy systems could be dedicated to one product, e.g., potable water, or designed to deliver two or more products or services, e.g., electricity and actinide management services or hydrogen and electricity.

The following sections focus on the case of a nuclear energy system producing electricity, process heat (for hydrogen), and/or actinide management services to highlight the key economic issues to be addressed. If both electricity and hydrogen are sold in competitive markets, there is no cost allocation problem: electricity is sold at the market-clearing price, as is hydrogen. The question becomes whether the technology will be competitive in an uncertain electricity market.

However, we cannot assume that electricity will necessarily be deregulated throughout the Generation IV life cycle in all the countries of deployment. If commercial deployment begins in 2030, deployment continues for at least 20 years, and the nuclear facilities have a 60-year life, Generation IV plants could be in use until the next century. While many states and countries have deregulated electricity, the deregulation movement has slowed after the electricity crisis in California. Further, in the United States, until the government develops a coherent electricity deregulation policy, re-regulation of electricity-generating assets will remain a possibility. Regulation, deregulation, and re-regulation in other countries is also uncertain. Therefore, a safe assumption is Generation IV nuclear systems will operate in both regulated and deregulated environments and the economic evaluation of these systems should consider both environments.

In this context, experiences in various European Union countries may provide insights into the operation of partially deregulated markets. Whereas the United Kingdom and Germany have deregulated their generation market sectors, France has been slow to deregulate, despite the general European Union deregulation directives. The evolution of the generation markets in these European Union countries, as well as others, will provide important lessons of how fully- or partially deregulated markets work, and the impacts of deregulation on the demand for new generating capacity.

Also, while hydrogen is now sold in competitive markets, as the hydrogen economy expands, hydrogen-producing technologies will be developed. Should these production technologies exhibit "natural" monopoly characteristics (generally technologies with large fixed costs), hydrogen could also be regulated. (The electricity industry expanded without interstate regulation in the United States. for its first 50 years.) On the other hand, there exist current alternative production methods of hydrogen, which will determine the marginal cost of this commodity for many years to come. If at any time during the Generation IV life cycle either electricity or hydrogen or both are regulated, DOE and GIF members should determine the appropriate (equitable) method of allocating costs between these joint products. These methods should be incorporated into the evaluation of Generation IV cost competitiveness and financial risks.

Finally, it is in the interest of DOE and parallel GIF agencies (as well as consumers of nuclear energy) to better understand the pricing of actinide management services. The value of actinide management will depend on national policies and priorities on radioactive waste management and disposal as well as on the cost of alternative options (e.g., disposal of spent fuel and/or high-level waste containing actinides). Economic comparisons should take into account the value of plutonium and other fissile materials arising from reprocessing spent fuel; savings, if any, on disposal costs; and social benefits of reducing the volume and toxicity of waste left to the stewardship of future generations.

3.4 Economics of Joint Production

Economic theory leads to the conclusion that each product should be priced to cover its variable (marginal) costs of production. On the other hand, allocating the fixed costs of production between different products (or classes of customers) involves considerations of *equity*, which are outside the scope of economic efficiency.

The issues raised by the economic assessment of Generation IV nuclear energy systems providing more than one product may be illustrated by the following very simplified example. Consider a situation in which a particular Generation IV technology produces electricity and actinide management services. Assume that (1) the cost of an electricity-only power plant is \$1B, (2) the cost of an actinide management-only facility is $1B, and (3) the cost of the joint-production system is $1.5B. How should the fixed costs of the joint facility be allocated between the two missions?

On the one hand, the minimum amount that should be allocated to actinide management is $500M, the difference between the power-only plant and the joint-production plant. Similarly, the minimum amount that should be allocated to electricity production is $500M, the difference between the actinide management-only facility and the joint-production plant. On the other hand, the maximum amount that should be allocated to actinide management is $1B, the cost of the actinide management-only facility. Similarly, the maximum amount that should be allocated to electricity production is $1B, the cost of the electricity-only plant. The key question then is should one mission be charged the bulk of the difference between $500M and $1B and, if so, which one, or should they split the difference evenly?

Economic methods exist to determine how best to allocate fixed (or common capital) costs, taking into account the specific objectives and priorities of producers, consumers, and society as a whole. The relevance of such methods for the economic assessment of Generation IV systems providing multiple products for multiple missions should be investigated and their application tested on the systems selected by GIF.

3.5 Electricity and Hydrogen

The economic analysis of the joint production of electricity and hydrogen using nuclear energy has not yet been standardized. (Much more work has been done on the production of electricity and heat; see, for example, Marecki 1988.) While some hydrogen production systems have been proposed, the costs and output are not well specified. The tradeoff between the use of heat to produce hydrogen and residual heat to produce electricity is also not well understood. Simple, standard economic models must be developed to evaluate these tradeoffs under various regulatory and competitive environments and hydrogen end uses. At the same time, it is critical to the Generation IV effort to understand supply (industry cost structure) and demand (including alternatives) for hydrogen, and how this market will change in this century.

There also appears to be confusion regarding the economic analysis of electrolysis. There is no large-scale electrolysis technology that requires a particular generation technology. The source of electricity for most (non-remote) electrolysis will come from a transmission grid. Therefore, whether electricity is regulated or deregulated, the cheapest source of electricity will be used first. Nuclear power technologies that only produce electricity must compete with all other electricity generation technologies in supplying electrolysis demand. What is required is an analysis of how hydrogen production will change the demand for electricity. If this demand is primarily for reliable base-load, then nuclear technologies will be more competitive.

Further, the engineering-economic analysis of particular high-temperature Generation IV technologies must consider the economic viability of systems that use (1) high-temperature for either electricity or thermochemical hydrogen production, and/or (2) a load-leveling cycle to produce electricity or hydrogen depending on demand. In this situation, electricity could be produced during periods of high demand (e.g., from 6 a.m. to 10 p.m.) and hydrogen could be produced during periods of low demand (e.g., from 10 p.m. to 6 a.m.). At present, nuclear power is used to cover base load because of its high fixed costs and low variable costs, and because current reactors are not readily compatible with frequent changes in power levels, as required in load following. The capability to produce either electricity or hydrogen with high-temperature ensures continuous production to cover fixed costs and allows the plant operator to maximize profit because hydrogen is produced and stored when the value of electricity is low.

3.6 Electricity and Actinide Management Services

A second area that requires analysis is the joint production of electricity and actinide management services. Because spent nuclear fuel contains special nuclear materials, governments will be involved in ensuring actinide management services throughout the life cycle of Generation IV nuclear energy systems.

Consider a fast reactor that produces electricity and actinide management services. Assume that the electricity market is competitive and electricity is sold at the market-clearing price. With this price, some fixed costs (e.g., the costs of construction) of the nuclear power system are recovered. If, however, not all of the capital costs will be recovered at prevailing electricity market prices, how much should society be willing to pay for actinide management?

In economic terms, the price elasticity of demand for actinide management depends on the alternatives available to users, i.e., governments and the power industry. The demand of governments for actinide management services is linked with national policy on radioactive waste disposal and alternative solutions available (e.g., geological disposal of spent fuel). Each GIF country has its specific policy and available alternatives that must be reflected in the economic analysis. Similarly, the price elasticity of the commercial nuclear power industry will depend on alternative spent fuel management options.

Actinide management, together with fulfilling a mission-critical service for society, involves the recycle of nuclear fuel, providing additional energy and thereby revenues. The issue of its economic assessment can be addressed as one of allocating the costs of reprocessing and waste disposal. Therefore, the economic analysis should consider the tradeoffs between (1) open-cycle systems with constrained geologic disposal, and (2) closed-cycle systems that could relieve constraints on geologic disposal and provide more energy out of the same amount of initially mined uranium. The economic analysis should give guidance on prices charged for actinide management services.

3.7 Electricity and Potable Water Production

The example of potable water production illustrates the need for a specific economic approach in assessing the viability and performance of Generation IV systems aiming at supplying products and services other than electricity. In several regions of the world, potable water is forecast to become a scarce commodity in high demand during the first quarter of the 21st century. Although desalination, using nuclear or fossil-fueled power plants, is seldom economically competitive today, the increasing demand is likely to create a viable market for the production of potable water.

The reject heat from a power plant (which is currently wasted) could easily be diverted to a desalination bottoming cycle at plants located near seawater or brackish water supplies. In a deregulated market, this provides for a storable energy product and an additional revenue source.

Very little R&D is needed to adapt nuclear reactors for this purpose (desalination) and extensive experience already exists at numerous LWRs (Japan) and LMRs (Russia). Heat rejected from LWRs and LMRs can be conveniently used in the Reverse Osmosis preheating configurations because the membranes can efficiently operate at about 50°C. For high temperature reactors rejecting heat at 100°C and above, emphasis could be placed on distillation concepts that effectively use higher temperatures to increase the amount of water produced per unit of thermal energy.

Generation IV reactors could be coupled to either of two competing and currently most utilized desalination technologies: the Multiple Effect Distillation Process (MED) and the Reverse Osmosis (RO) membrane process. However, integrated systems using these technologies are substantially different in their design and optimization. Economic analyses are required to evaluate the cost and benefit in future markets of the necessary adaptations to reactors designed for electricity generation.

4. MODELING THE ECONOMICS OF GENERATION IV SYSTEMS

According to the economic goals of the GIF, nuclear energy systems should have a life cycle cost advantage over other energy sources. Assessing this advantage at the viability or performance stage raises a number of issues owing to uncertainties of the economics of nuclear energy systems that have not been built and operated. Also, there are uncertainties regarding the cost and price of alternative options that may be available in the market when Generation IV systems will be ready for deployment.

Methods and computer tools exist to estimate the cost of reactor types under development, for which there is no concrete industrial experience on which cost assessment can be based. Those tools were implemented in the early stages of nuclear energy deployment and updated on a regular basis when needed, as long as new nuclear reactor designs were being developed. Since most nuclear power plants built recently are evolutionary, based upon designs and technologies already mature and proven, there has been no need to modify and update the cost assessment tools since the early 1990s (ORNL 1993).

The innovative nuclear systems may require new tools for their economic assessment since their characteristics may differ significantly from those of current Generation II & III nuclear power plants. In particular, the current economic models are not designed to consider various issues related to the construction and operation of modular plants. Also, the development of new tools for cost assessment may benefit from the evolution of computers and software.

The benefit of such tools is to improve the reliability of economic assessments made at an early stage of concept development. Thereby, designers have a better understanding of how they compare with alternatives (nuclear reactors or other technologies) and may identify areas deserving specific attention to improve their economic performance.

4.1 Integrated Model for Electricity Generation Cost

To help address those issues, the ECG recommends the implementation and use of an integrated model (calculation tool) capable of providing flexible and transparent life cycle cost estimates for Generation IV nuclear energy systems and alternatives. The adoption of a standardized methodology for cost calculations is a prerequisite for a fair comparison among different nuclear energy systems and between those systems and alternative options for electricity generation. The levelised-lifetime cost methodology calculates costs on the basis of net power supplied to the station busbar. The model proposed by the ECG is based on a methodology that allows sensitivity studies covering a wide range of country-specific contexts and possible futures regarding alternative competitors. We begin by reviewing the present state of this methodology.

Applied to generation costs, the levelised-lifetime methodology provides costs per unit of electricity generated equal to the ratio of total lifetime expenses and total expected generation, both expressed as present values. These costs are equivalent to the average price that would be paid by consumers to repay the investor for the capital and the operator for O&M and fuel expenses, discounted at the rate of return.

The methodology discounts the time series of expenditures and incomes to their present values in a base year by applying a specific discount rate. The discount rate takes into account risk and the time value of money, see Rothwell and Gomez (2002, Chapter 3). The discount rate that is considered appropriate for the power sector may differ from country to country, and from utility to utility. The appropriate discount rate can be equal to:

- Rates of return that could be earned on typical investments

- A rate required by public regulators incorporating allowance for financial risks and/or derived from national macroeconomic analysis

- A rate reflecting the tradeoff between costs and benefits for present and future generations.

The use of a flexible model permits sensitivity studies using a range of discount rates representative of various contexts.

To assess the economic advantage (or disadvantage) of nuclear energy systems over alternatives, all costs facing the utility that would influence its choice of generation options, should be taken into account. In particular, the costs associated with environmental protection measures and standards, such as the cost of safety and radiation protection measures for nuclear systems, are included in life cycle costs. On the other hand, external costs that are not borne by the utility, such as costs associated with health and environmental impacts of residual emissions, are usually not included. However, if external costs are borne by the public or the environment, they should be taken into account from a public (or national government) point of view when choosing among nuclear technologies.

The analytic algorithms applied in computer tools designed for calculating levelised-lifetime costs of generating electricity generally assume that expenses and earnings are discrete and occur on an annual basis. As most expenditures and incomes occur in multiple instances during the course of the year, rather than one single event, annual costs have been assumed to occur at midyear for discounting purposes. Taking into account uncertainties in cost elements at the viability or performance stage, this approximation is unlikely to affect significantly the reliability of calculation results.

The expression used to calculate (for each power plant) the levelised electricity generation cost (EGC) is the following:

$$EGC = \sum_t [(I_t + M_t + F_t)(1+r)^{-t}] / \sum_t [E_t (1+r)^{-t}]$$

where

EGC	=	Average levelised-lifetime electricity generation cost per kWh
I_t	=	Capital expenditures in the year t
M_t	=	Operation and maintenance expenditures in the year t
F_t	=	Fuel expenditures in the year t
E_t	=	Electricity generation in the year t
r	=	Discount rate
$\sum_t$	=	The summation over the period, including construction, operation during the economic lifetime, and decommissioning of the plant.

Cost elements are expressed in real monetary terms (e.g., real dollars). Construction and operation schedules are defined for each option considered (nuclear energy system or alternative) according to its technical characteristics. A unique date is selected as the base year for discounting purposes. Although this date does not affect the leveled cost comparison between different plants, the absolute values of levelised cost will differ from year to year in periods of inflation or deflation.

Other sections of the report deal with methods for estimating each cost element (i.e., investment, O&M, and fuel for Generation IV nuclear energy systems). Capital expenditures include refurbishment and decommissioning costs. Escalation rates for operation and maintenance and fuel costs are taken into account if applicable.

With regard to outputs from the power plants, electricity generation in the year t is calculated taking into account the net capacity of the unit and assuming a lifetime load factor. At the stage of performance evaluation, if the information is available, the model may include load factor evolution over time. As with annual expenditures, annual generation is assumed to occur at midyear for discounting purposes. The cost calculations should be flexible enough to consider plant capacity uprates, most likely occurring in conjunction with other major capital improvement program, such as steam generator replacement or life extension.

The economic merits of different candidate power plants are derived from the comparison of their respective average levelised-lifetime costs. Technical and economic assumptions underlying the results are transparent and the method allows for sensitivity analysis showing the impact of different parameters on the relative competitiveness of the alternative technologies considered.

An alternative to discounting to present values and deriving total costs is to allocate capital charges to projected electricity output. (This approach was taken in the calculation of average cost in the Final Screening Methodology.) This can be done either by calculating depreciation and interest charges, which yields a variable decreasing annual sum to be recovered from the plant output, or by amortizing the capital and interest to yield a constant sum for each year of the plant lifetime (e.g., calculated with the Capital Recovery Factor).

The latter yields a capital charge per unit of output, which (when added to the production costs per kWh) is equal to the levelised-lifetime cost derived from the total present-worth cost calculations (provided the interest on capital and discount rates employed are the same, and inflation is eliminated from the computation).

4.2 An Engineering Model for Plant Capital Cost

Engineering capital cost models are based upon detailed information on current procurement and construction practices and schedules. They provide a consistent framework to account for each cost item (see Table 1 for an example of a Generation III system) and calculate total capital costs reliably and transparently.

Adapting existing engineering models, including those developed in other industrial sectors, developing new computing techniques, and allowing adaptation to country-specific contexts would facilitate the economic assessment of Generation IV systems within a harmonized framework during their early development phase. R&D in this field could be undertaken as a crosscutting activity within the Roadmap follow-up programs.

The application of advanced information technologies would help to better estimate and reduce capital and operating costs, and to improve plant configuration management over its life cycle. Advanced engineering methods and project management tools are needed to:

- Help minimize design costs and the extent of site rework
- Help minimize the impact of site-specific and late-design changes
- Permit module fabrication in several locations and ensure necessary materials are available
- Reduce site craft labor (low productivity) man-hours.

Table 1. Example of construction cost model.

Average Capital Cost of Next Two ABWR Units (built in USA)	
Direct Cost Accounts	***millions of US$***
21 Structures and improvements	*430*
22 Reactor Plant	*520*
23 Turbine Plant	*230*
24 Electrical Plant	*150*
25 Miscellaneous Plant	*45*
26 Main Heat Rejection System	*45*
Total Direct Costs	***1,420***
Indirect Cost Accounts	
91 Construction Services	*250*
92 Engineering Home Office	*70*
93 Field Office Services	*190*
Total Indirect Costs	***510***
Total Overnight Construction Costs	***1,930***
Total Overnight Construction Costs/kWe	***~ $ 1,400***
Contingency	*125*
Owner's Cost	*200*
Total Capital Cost	***2,255***
Total Capital Cost in US$/kWe	***~ $ 1,600***

NEA (2000, p. 99)

Relevant R&D programs in this field include: development of document and drawing management, materials management, and other project management tools; and development of enhanced computer-aided design and drafting (CADD) tools and techniques.

4.3 Estimation of Modular versus Monolithic Plant Capital Costs

The interest in the construction of small modular nuclear plants, in parallel with the construction of large monolithic plants, raises the issue of how to account for the costs of these two types of plants equitably. There are significant differences in the circumstances that lead to the decision to build several small modular plants versus one large monolithic plant. Consequently, there are cost factors involved in the construction of a small modular plant that are not encountered, and not accounted for, in the "conventional" cost computation of a large monolithic plant. To make a reasoned economic decision as to which plant to select, it is essential that all the cost factors involved be considered.

Usually specific plant capital costs, expressed in currency per installed kWe (e.g., $/kWe), are lower for a large plant, due to economies of scale. Yet, there are significant advantages to the early construction completion and start-up of smaller plants (i.e., an earlier revenue stream) that do not always appear in the standard cost accounting system developed for large monolithic plants.

Several cost factors should be accounted for when comparing the economic advantages of large versus small and modular nuclear power plants on an equal basis. Such factors are reviewed briefly below. Economic models to be developed and used within the Generation IV Roadmap follow-up framework should reflect these factors to ensure a fair assessment of the potential economic benefits of small modular systems versus large monolithic systems. More work must be done to account for the following differences between small and large plants properly.

4.3.1 Load Management

Small modular plants built on a short time schedule can be located at plant sites to satisfy small increments of local load growth. A large monolithic plant can only fit the load growth projection of a larger region.

4.3.2 Early Revenue Stream

Small modular plants with short construction lead-times can bring in a revenue stream, from the electricity sales, earlier than would be the case with a large monolithic plant with longer construction lead-time. This has implication for the willingness to lend and for the rate of interest required.

4.3.3 Risk Management

Both capital-at-risk and time-at-risk (length of the risk period) factors are lower for a small modular plant with a short construction lead-time than for a large monolithic plant with a longer construction period. Since the capital at risk at any point in time is lower for a series of small modular units than for a large monolithic plant, the risks associated with unexpected delays, failure to perform, or change in requirements, if they emerge, would have less pronounced financial impacts. This has the potential to improve the lender's willingness to lend to builders of smaller plants.

4.3.4 Modularity

Since plant system structures and components are smaller for the small plants, maximum use can be made of modular equipment and system manufacture, either in a remote factory or in an on-site fabrication shop. In both cases, lower productivity of on-site labor force is replaced by higher productivity factory labor thereby improving reliability of modules. These benefits do, however, come with the extra cost of constructing the module factory, higher salaries for the factory as compared with the on-site labor force, and incremental costs of completed module shipment to the construction site. Modern cost accounting should include such modular construction cost issues. The ECG recommends funding of the conceptual engineering design of a modular construction system that can be referenced by the designers of small modular plants in determining overnight construction costs.

4.3.5 Standardization

It is easier to standardize the design of a large number of small modular plants than a smaller number of large monolithic plants. The basic plant design cost is smaller for a small plant than for a large plant because of a smaller number of systems, calculations, and design drawings. Assuming that modular plants are ordered and built in large series, the basic design cost can be divided over a larger total capacity than in the case of a large monolithic plant that will be replicated only a few times. The benefits of standardization potentially could further extend to lifetime issues such as operator training costs, transfer of operating experience, roving maintenance and outage support costs, lower inventory of replacement parts, and generally lower O&M costs.

There is, however, a negative effect of standardization associated with a generic equipment malfunction or design error situations. Such occurrences may affect the entire fleet of standardized plants, rather than one unique plant design. Some of these potential pitfalls of standardization have been discovered in the largely standardized French nuclear power program (e.g., the control rod guide pins, or the cracked reactor vessel heads). Even here there exists a silver lining, in that once a technical fix is developed, it applies to the entire plant fleet within a series. It is thus possible to distribute the repair design cost among several plants and reduce the per plant cost.

4.3.6 Licensing

The cost of plant safety licensing could be divided over a larger number of small plants rather than over the smaller number of large monolithic plants. This cost could be significant. For example, the U.S. Nuclear Regulator Commission (NRC) Design Certification of the Advanced Light Water Reactors has averaged $160 million per design. However, the construction of several modules, even on the same site, may require successive license requests and increase the total licensing cost of a modular plant.

4.3.7 Incremental Lifetime Costs

The total costs of cooling water requirements, spent fuel disposal, low and intermediate waste handling, insurance, life extension, and decommissioning are lower for small modular plants than for a large monolithic plant. Generally, lower cooling water requirements are ascribed to the smaller modular plants since these plants are designed to higher energy conversion efficiencies than the large monolithic plants. However, specific costs (per kWe installed or per kWh produced) tend to be higher for smaller than for larger plants. It should be determined how these costs would compare for an equal capacity plant made up of one monolithic plant or several small modular plants on a case-by-case basis. The cost accounting system should be modified to include such cost components from a large number of small plants.

4.3.8 Ancillary Service Costs

Ancillary services include the reserve capacity that must be procured whenever a new plant is added to the electric network, to maintain service reliability. In general, a constellation of small modular plants would require smaller reserve capacity than would a large monolithic plant. This is because the reserve capacity required is proportional to the smallest plant capacity that could experience an outage. In deregulated electricity market conditions, usually the plant owner must furnish the ancillary services for each plant brought on line. Thus when ordering a small modular plant or several thereof, the cost of ancillary services procurement would be lower than would be the case when committing to a large monolithic plant.

4.3.9 Replacement Opportunities

Small modular plants could be more appropriate replacements than large monolithic plants for the small capacity fossil-fired plants that will be withdrawn from base load generation over the next two decades due to aging, equipment deterioration, or rising fossil fuel prices.

These factors, as well as others, should be analyzed when comparing small modular versus large monolithic nuclear energy systems. However, a number of these factors cannot be assessed adequately before the deployment phase of a given system since they depend on the context (e.g., grid size, alternative options to be replaced, electricity market demand and conditions). However, market conditions can be simulated to assess the economics of reactor size.

4.4 Cost Model for Nuclear Fuel Cycle

Since fuel cycle cost represents around 20% of the levelised cost of nuclear electricity generation in most current nuclear power plants, reducing this cost will help meeting Generation IV economic goals.

Methodologies and computer tools for calculating fuel cycle costs are relevant in this regard. Also, fuel cycle cost models can play an important role as decision aiding tools for optimizing fuel cycle options, taking into account the tradeoffs between sustainability, economics, safety and reliability, and proliferation resistance and physical protection.

If the levelised-lifetime cost methodology is adopted for estimating total generation cost, adopting the same approach for fuel cycle cost is a prerequisite for ensuring consistency. Moreover, since payments for materials and services within the nuclear fuel cycle are occurring over many years, the timing, as well as the values of each payment in constant (inflation free) money terms, is important. The levelised cost method provides a common basis.

Economic modeling of the nuclear fuel cycle covers many steps corresponding to materials and services required either before or after fuel loading. The cash outflow for fuel cycle materials and services begins before the nuclear power plant starts to generate electricity and continues well after its shut down. The exact timing of payments for uranium, fuel fabrication, reprocessing, etc., depends on the fuel cycle chosen and the associated lead and lag times for each of the fuel cycle components.

To calculate the overall fuel cycle cost, the magnitude of each component cost and the appropriate point in time when it occurs must be identified. Mass flows and fuel cycle lead times result, essentially, from the technical characteristics of the nuclear energy system considered. (It should be noted, however, that economic criteria might be taken into account in designing and/or choosing a fuel cycle.)

For “classic” fuel cycles, the main steps are uranium production, conversion, enrichment (not needed for natural uranium fuel cycles), fabrication, and spent fuel disposal for the once-through option. In the recycle option, the back-end of the fuel cycle includes reprocessing, re-fabrication, and disposal of high-level waste from reprocessing. Generally, for modeling purposes transportation costs are not accounted for separately but integrated in the different steps, e.g., spent fuel transportation lead-time and cost will be included in reprocessing lead time and cost for the recycle option.

Technical characteristics needed to carry out the calculation include:

- The mass of uranium contained in the fuel when loaded in the reactor
- Losses at conversion, enrichment, and fabrication steps
- Enrichment of the fuel in ^{235}U and tails assay of the enrichment plant
- The possibility of using blended-down highly enriched uranium from previous military stockpile as the source of enriched fuel, rather than using enrichment services
- All lead times at the front end of the fuel cycle to fuel loading in the reactor.

Exogenous economic input data include prices for uranium, enrichment, blending down, and fabrication, as well as the expected price escalation over time. Once all the cost components have been calculated they are discounted back to a selected base date and added to arrive at a total fuel cost in present value terms.

Non-classical fuel cycles to be considered within Generation IV Road Map would require the adaptation of existing models, or the design of new models, to include different steps, materials, and services. The economic aspects are important for assessing the viability and performance of non-classical fuel cycles. Therefore, the ECG recommends R&D focus on modeling non-classical fuel cycles.

The development of an economic model including simulations of the simple once through uranium fuel cycle and alternative fuel cycle (recycling, actinide burning, etc.) is extremely important in assessing the economic benefits of nuclear energy systems and fuel cycle options.

5. R&D DEPLOYMENT STRATEGIES AND PLANNING CONSIDERATIONS

Implementation of the R&D recommendations from the Generation IV Roadmap will likely involve the commitment of several billion dollars in funds over several decades. The challenge is to deploy these research funds in an optimal way, to maximize R&D results as well as characteristics of the developed technological options within time and budget constraints. The identification of an optimal R&D deployment strategy (i.e., research topics, nuclear systems considered, timing of research, organizations involved, method of solicitation) is an issue that is as important as the identification of the key technical R&D issues that must be addressed.

Generation IV R&D activities could be distributed in three ways:

- Centered on Generation IV nuclear energy systems
- Focused on key enabling technologies and topics
- A combination of both.

The first approach could allow for development of a complete system for future use, while the second approach would involve generic R&D that could be used for some or all Generation IV nuclear energy systems, but may not lead to the development of a specific nuclear energy system. The third approach, where neither specific systems nor specific R&D areas are the only focus, would link research on enabling technologies with the specific nuclear system needs. Table 2 below shows an example of this integrated approach.

In this approach, each of the six Generation IV nuclear energy systems selected by the GIF would be considered separately with the key enabling technologies addressed in a time sequence. The most important R&D topics would be addressed first with clear and concise intermediate outcomes identified and specifically related to the R&D funds to be expended as well as the subsequent research activities required. Appendix A outlines a specific alternative R&D deployment process approach that is used by a major reactor vendor.

Table 2. R&D Deployment Strategy.

System	Enabling Technology (V)	Enabling Technology (V)	Enabling Technology (P)	Enabling Technology (O)	R&D Resource (Demo Plant Y/N?)
SCWR (TWG-1)	Materials & Corrosion ~$0.3 billion	Reactor Safety ~$0.2 bill	Reactor Stability <$0.1 billion	System Design ~$0.2 bill	< $1 billion (probably)
GFR (TWG-2)	Fuel Cycle	Materials & Corrosion	Reactor Safety	System Design	>$1 billion (probably)
VHTR (TWG-2)	Materials & Corrosion	Fuel Cycle			>$1 billion (yes)
LMR (TWG-3)	Fuel Cycle	Reactor Safety			>$1 billion (probably)
Pb-Alloy (TWG-3)	Materials & Corrosion	Fuel Cycle			>$1 billion (yes)
MSR (TWG-4)	Fuel Cycle	Corrosion			>$2 billion (yes)

The Supercritical Water Reactor (SCWR) concept is noted with the total estimated level of funding in each particular R&D area. The SCWR concept would first be expected to address materials and corrosion research that would establish the feasibility of robust fuel and structural materials, as well as reactor safety studies. These would probably begin at modest levels in out-of-pile experimental facilities. If the interim research goals were satisfied and materials selected were proven to be robust in a supercritical water environment for corrosion and safety (neutronics and heat transfer), then more extensive (and costly) in-pile tests could begin. Simultaneously, reactor stability and systems design studies could get underway once shown to be technically feasible.

The R&D deployment strategy should be aligned with the likely deployment of nuclear reactor systems that are evolutionary in nature, as well as the progression of fuel cycles over the next few decades (e.g., once-through, mixed-oxide, partial recycle, and full recycle). In addition, there could be other potential energy products developed for particular customers.

Recently, DOE issued its Near-Term Deployment report, and the GIF more recently adopted a similar International Near-Term Deployment strategy. In each case the expectation is that a group of reactor systems (e.g., ABWR, AP1000, GTMHR, or PBMR) are available for deployment in the next decade. These systems are for evolutionary concepts that offer significant economic improvements as well as improved safety. They will provide a technological and economic base that some Generation IV systems (SCWR, GFR, and VHTR) will utilize, and their development will contribute to reducing the R&D costs for gas-cooled and water-cooled Generation IV systems. Improved sustainability will occur as concurrent fuel-cycle developments provide for improved fuel burn-up limits. Additional fuel-cycle improvements (mixed-oxide fuels, partial recycle, and full recycle) are possible if fuel-cycle economics are favorable and if sustainability issues increase in importance.

It is the evolution of sustainability requirements and the improvement and economics of advanced fuel-cycles that will determine the necessary timing of the introduction of certain types of these advanced reactor concepts. The same logic would apply to the introduction of joint energy products with nuclear systems. In all cases the competitive economic environment will determine what is ultimately feasible.

6. GENERIC ECONOMIC R&D RECOMMENDATIONS

The reliability and consistency of economic assessments to be carried out during the GIF R&D program are key to the success of Generation IV systems. Assessing and comparing the economic performance of Generation IV systems under development is essential to support decision-making regarding R&D on alternative reactor and fuel cycle options. Farther down the road, understanding how Generation IV systems compare with other nuclear energy systems and other energy supply technologies will be a prerequisite for their successful commercial deployment.

ECG recommends the investigation of five main economic areas within the Viability Evaluation of Generation IV systems (see Figure 1). It includes research on reliable and flexible approaches to monitoring fund allocation within the GIF research programs to maximize the outcomes and modeling of all economic aspects of nuclear energy systems.

The focus of the recommended R&D is the design and implementation of economic models conceived as decision aiding tools to be used within the GIF R&D programs for the development of Generation IV systems and beyond, for the continued economic assessment of nuclear energy systems of the next generation.

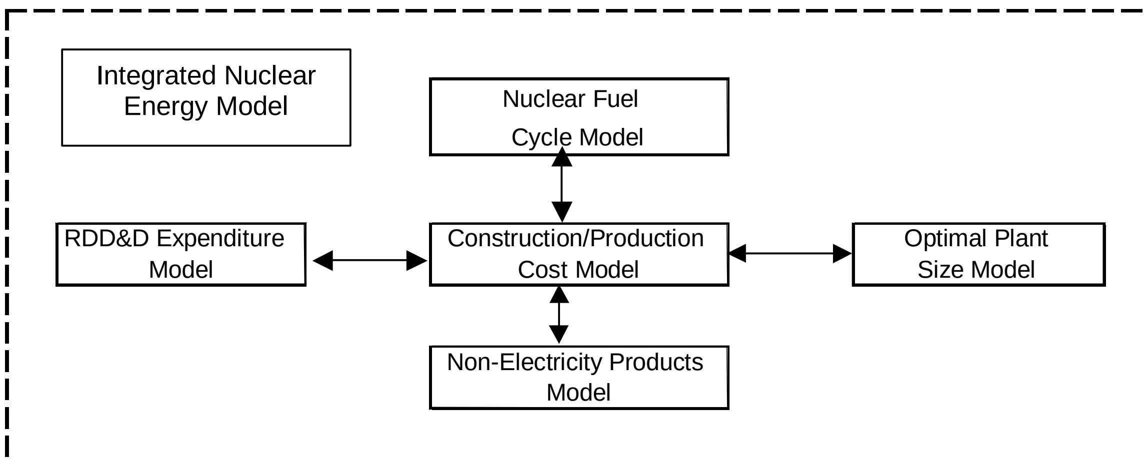

Figure 1. An Integrated Nuclear Energy Model

Each of the five economic areas outlined in Figure 1 can be addressed by a specific model/computer tool. Those five models could then be integrated to provide a global economic assessment tool adapted to the Viability and Performance phases of the GIF project.

Although methods and computer tools exist to estimate the cost of nuclear energy systems, the models available must be updated and adapted to become fully relevant and reliable for the economic assessment of Generation IV nuclear systems that have innovative characteristics differing from those of current Generation II & III nuclear power plants. Also, within GIF R&D programs, the comparison between alternative nuclear systems will be needed. This aspect is not covered comprehensively by current economic models designed primarily to compare nuclear energy with fossil alternatives.

Table 3 summarizes generic economic issues and gaps and the R&D activities proposed by the ECG to address those issues within the GIF Roadmap framework. In connection with the Generation IV economic goals, all the gaps identified are relevant for concept viability. The Optimal Size Model and the Integrated Nuclear Energy Model are relevant for concept performance also.

Table 3. Generic Economic R&D Scope.

Specific Issue	Economics Generic Gap/Issue: Gap Label	Brief Description of Gap/Issue	Signific. of Gap (a)	TRL Now (b)	R&D items: Activity Label	Brief Description of R&D Activity	Priority (c)	Time (d)	Estimated Cost Range (Million USD)
Construction-Prduction Cost Model	Cost	Current economics models lack completeness for new Generation IV reactor concepts	V	3	Cost	Update a construction-production cost model (e.g., ORNL) for comparison of GEN IV concepts	2	S	< $ 0.50
Fuel Cycle Economics	FC	Current fuel cycle models lack completeness to allow for MOX, partial, and full recycle and fuel cycles for innovative reactors	V	3	FC	Update a Fuel Cycle Cost Model, e.g., NEA/OECD	2	S	< $ 0.50
Production Cost Model for Multiple Energy Products	NEP	The issue is how to allocate costs of a nuclear energy system when it produces electricity and/or other porducts, e.g., process heat or actinide burning services. Given these costs, what is optimal product mix? This issue is crucial in a regulated environment for one or several of the joint products.	V	1	NEP	Develop & implement a methodology for estimating the cost of joint products of a nuclear energy system, e.g., assigning fixed costs between various joint products.	1	S	< $ 0.50
RDD&D Optimization Model	RDDD	A more integrated approach should be considered, where specific reactor concepts and specific RDD&D areas are a combined, which links research on enabling technologies with specific reactor concepts needs to optimize resource allocation..	V	1	RDDD	Develop an integrated RDD&D deployment approach for GIF	1	S	< $ 0.50
Optimal Plant Size Model	Size	Some GEN IV systems are modular reactors and other large size units. Economic assessments and comparisons should reflect the benefits and drawbacks of each approach, e.g., econmy of scale versus series effect, as well as the impacts of improved design (CADD) and fabrication methods and new materials on costs. Current construction-production cost models do not alllow for such comparisons.	V & P	1	Size	Develop a capital cost model that includes consideration of optimal plant scale (modularity, pre-fabrication methods as well as plant size). Produce generic design of a reactor fabrication facility.	1	S	< $ 3.0
Integrated Nuclear Energy System Model	INES	Current economics models lack completeness for new Generation IV reactor concepts	V & P	1	INES	Incorporate results of these models into a cost model that would be part of an integrated economics model for comparison of GEN IV concepts	3	S	< $ 1.0
Total cost									< $ 6.0

(a) Indicate relevance of technology gap: V = concept viability; P = performance; O = design optimization.
(b) Technology Readiness Level (1, 2, 3, 4, or 5); see EMG Final Screening Document
(c) Indicate priority of R&D task:
1 = critical (needed to resolve a key feasibility or viability issue)
2 = essential (needed to reach a minimum targeted level of performance, or to resolve key technology or performance uncertainties)
3 = important (needed to enhance performance or resolve the choice between viable technical options)
(d) Indicate time required to perform R&D: S = short (<2 y), M = medium (2-5 y), L = long (5-10 y), VL = very long (>10 y)

Within each R&D activity, preliminary tasks will include a survey of existing studies and available tools. The survey will cover not only literature and experience in the nuclear energy sector but also in related energy and industrial fields where issues such as cost allocation for multiple-product plants have been addressed already.

6.1 Construction/Production Cost Model

Central to the economic evaluation of nuclear energy systems is the Construction/Production Cost Model (or "Cost Model"). ECG recommends updating an existing construction/production cost model, such as the Oak Ridge National Laboratory's (ORNL) model based on *Cost Estimate Guidelines for Advanced Nuclear Power Technologies* (ORNL 1993). The levelised-lifetime cost methodology adopted in the ORNL model, and others, is relevant for GIF R&D programs where the key issue is to assess whether the selected nuclear energy systems meet the economic goals of Generation IV.

This methodology provides a cost per unit of electricity generated equivalent to the average price that would be paid by consumers to repay the investor for the capital and the operator for O&M and fuel expenses, at a discount rate equal to the rate of return. The costs calculated by this type of model include all aspects of construction (e.g., sequencing and duration of plant construction or fabrication tasks), refurbishment (also known as capital additions), and decommissioning costs.

For the GIF R&D programs, the Cost Model should be adapted to handle innovative systems including those with co-location of reactor and fuel cycle facilities. Because of the scheduled deployment date of Generation IV systems, the levelised-lifetime cost methodology might need to be complemented by approaches more adapted to deregulated electricity markets.

6.2 Nuclear Fuel Cycle Cost Model

The model for fuel cycle cost calculation provides information to the Cost Model, which takes the cost of front-end and back-end of the fuel cycle as inputs. It can play an important role as a decision-aiding tool for optimizing fuel cycle options taking into account tradeoff between sustainability, economics, safety and reliability, and proliferation resistance and physical protection.

The Nuclear Fuel Cycle Model (or *Fuel Model*) should calculate costs associated with both the front-end and back-end of the nuclear fuel cycle using a methodology compatible with the approach adopted in the Cost Model. A representative of this type of model capable of handling "classic" fuel cycles including reprocessing and recycling in water or fast reactors, is the Organization for Economic Cooperation and Development/Nuclear Energy Agency (OECD/NEA) tool used for preparing the report *The Economics of the Nuclear Fuel Cycle* (1994). This model, however, is not adapted to innovative fuel cycles, including minor actinide partitioning and transmutation.

At the viability stage, the assessment of innovative fuel cycle economics is essential and requires the updating of existing models. For classic fuel cycles the main steps are uranium production, conversion, enrichment (not needed for natural uranium fuel cycles), fabrication, and spent fuel disposal for the once-through option. In the recycle option, the back-end of the fuel cycle includes reprocessing, re-fabrication, and disposal of high-level waste from reprocessing. Non-classical fuel cycles will require the adaptation of existing models or the design and implementation of new models to include different steps, materials, and services.

Updated models should include recent developments in the understanding of reprocessing and repository economics. They should be flexible enough to consider technologies that rely on integrated energy production/fuel reprocessing, such as the Molten Salt Reactor. The fuel cycle model will provide front- and back-end costs to the Cost Model. The development of an economic model including simulations of the simple once-through uranium fuel cycle and alternative fuel cycle (recycling, actinide burning, etc.) is extremely important in assessing the economic benefits of alternative nuclear energy systems and fuel cycle options.

6.3 Model for Non-Electrical Products

The Non-Electrical Products Model would address multiple energy product economics, including tradeoffs, such as those between low-cost electricity generation, actinide minimization, and/or hydrogen production. The economic analysis of the joint production of electricity and other energy (non-electrical) products is not well understood. For example, the economics of joint electricity and hydrogen production using nuclear energy has not yet been fully analyzed. Similarly, the joint production of electricity and actinide management services requires additional analysis. Because most of the Generation IV technologies can be used to address more than one mission, crosscutting economics research must define standards for accounting for the costs of more than one product. Standard economic models must be developed to evaluate these tradeoffs under various regulatory and competitive environments. It is critical to the Generation IV effort to understand the supply (industry cost structure) and demand (including alternatives) for hydrogen and actinide management, and how this market will change during this century. In particular, using Generation IV technologies to manage actinides requires the specification of the feedback mechanism between the production of spent nuclear fuel and its life cycle management.

6.4 Optimal Plant Size Model

To help determine the optimal size of the nuclear energy production plant, the **Optimal Scale Model** would analyze issues associated with modularity and associated economies of serial production-construction of nuclear energy plants as compared with economies of scale brought by large units.

Another issue that has not yet been resolved in the assessment of advanced reactor technologies is whether mass production of small reactors can compensate for the cost advantages from scale economies of large units or plants. There are cost factors involved in the construction of a small modular plant that are not encountered, and not accounted for, in the "conventional" cost computation of a large monolithic plant. To make a reasoned economic decision as to which plant to select, it is essential that all the cost factors involved be considered. In general, specific plant capital costs, expressed in currency per installed kWe (e.g., $/kWe), are lower for a large plant due to economies of scale. Yet, there are significant advantages to the early construction completion and start-up of smaller plants (e.g., an early revenue stream) that do not always appear in the standard cost accounting system developed for large monolithic plants.

There are several specific cost factors that should be accounted for when comparing, on an equal basis, the economic advantages of large versus small and modular nuclear power plants. Such factors include (1) load management and reliability, (2) standardization and licensing, and (3) retiring plant replacement possibilities. Economic models should reflect these factors to ensure a fair assessment of the potential economic benefits of small modular systems versus large monolithic systems. More work must be done to properly account for the differences between small and large plants. While economics research in this area should be inexpensive, developing an economic-engineering model would require more resources. For example, research in this area could be extended to developing the conceptual engineering design of fabrication facilities and transportation systems.

6.5 Model for Allocating RDD&D Expenditures

The RDD&D (Research, Development, Demonstration, and Deployment) Expenditure Allocation Model, would provide guidance on optimal research, development, and demonstration paths to deployment of innovative nuclear systems. There appear to be no generally accepted representatives of this type of model in the nuclear industry.

Generation IV RDD&D recommendations will likely involve the commitment of several billion dollars in funds over several decades. Research involves answering basic scientific and engineering questions (related to Viability). Development involves the creation of conceptual designs. Demonstration includes prototype or demonstration plants. Deployment includes First-Of-A-Kind (FOAK) costs (see ORNL 1993 on the definition of FOAK versus Nth-of-A-Kind costs).

The management challenge is to spend the funds in an optimal way to maximize RDD&D results within time and budget constraints. The identification of an optimal implementation strategy (i.e., research topics, reactor concepts considered, timing of research, organizations involved, method of solicitation) is an issue that is as important as the identification of the key technical R&D issues that must be addressed. With an integrated RDD&D approach each of the Generation IV nuclear energy systems would be considered separately with the key enabling technologies addressed in a time sequence. A model is needed to test the sensitivity of the attainment of milestone dates with changes in the level of funding at each stage of research, development, demonstration, and deployment.

The R&D deployment strategy should be aligned with the likely deployment of evolutionary nuclear reactor systems, as well as the progression of fuel cycles over the next few decades, i.e., once-through, mixed-oxide, partial recycle, and full recycle, as identified in the FCCG reports. In addition, there could be other potential energy products developed for specific customers. Therefore, it is the evolution of sustainability requirements and the improvement and economics of advanced fuel-cycles that will determine the necessary timing of the introduction of these advanced reactor concepts. An RDD&D expenditure model should take this evolution and the changing competitive environment for energy production into account.

6.6 An Integrated Nuclear Energy Model

An Integrated Nuclear Energy Model, combining all of the nuclear-economic models described above, would provide a robust support for economic optimization within the Viability and Performance phases of the GIF project. DOE/EIA (Energy Information Administration) experience with the development of the National Energy Modeling System (NEMS, see DOE/EIA 2000) provides a framework for integrating components of an economic model. Also, the results of the Integrated Nuclear Energy Model can be compared with the results of NEMS (see, for example, *Annual Energy Outlook*, AEO, DOE/EIA 2001; note that the AEO forecasts energy use to 2020 only).

An integrated model is necessary to compare various Generation IV technologies. Also, it can answer optimal configuration questions, such as which fuel cycle is most suitable for each state of the world and optimal deployment ratios between members of a symbiotic set. The goal of integrating these models provides incentives to build common data interfaces between the models.

Further, none of these models address the problem of uncertainty, e.g., the uncertainty of cost and parameter estimates. During Generation IV's Final Screening Evaluation ranges, expected values, and probability distributions were identified for construction cost, construction duration, and production costs. From these, probability distributions for Average Cost and Capital-at-Risk were generated assuming no correlation between costs and duration. The Integrated Nuclear Energy Model should address these uncertainties. This can be done by specifying probability distributions for each of the uncertain inputs and allowing easy sensitivity analysis for each of the uncertain parameters. The model runtimes should be fast enough to allow decision makers to simulate probability distributions for each of the key outputs. These distributions can be compared for each Generation IV technology. Options that stochastically dominate alternatives can be pursued. When no option is stochastically dominant, i.e., probability distributions overlap, the model can help decision makers understand the tradeoffs between low-cost, high-risk options and high-cost, low-risk options. This will help them assess the value of reducing uncertainty through the allocation or reallocation of research funds.

6.7 Roadmap for R&D on Economics of Nuclear Systems

The ECG recommends that the models be developed before the Viability Evaluation. Figure 2 identifies the order of these tasks. During the first year,

1. The Construction-Production Cost Model should be updated using an existing, accepted model, such as ORNL (1993)

2. The Nuclear Fuel Cycle Model should be updated, using an existing, accepted model, such as NEA/OECD (1994)

3. Scoping reports should be done for the other models, leading to a Request for Proposals.

During the next two years

1. These updated models should be integrated

2. Work should proceed on the creation of models for Non-Electrical Products, RDD&D expenditure allocation, and optimal plant size.

During the last two years, all models should be integrated, addressing uncertainty. Further, if funds are available, we suggest the development of engineering designs of nuclear plant fabrication facilities. These designs should include expected costs and incorporated into the Integrated Nuclear Energy Systems Model. These models will aid decision makers in assessing the Viability of Generation IV technologies.

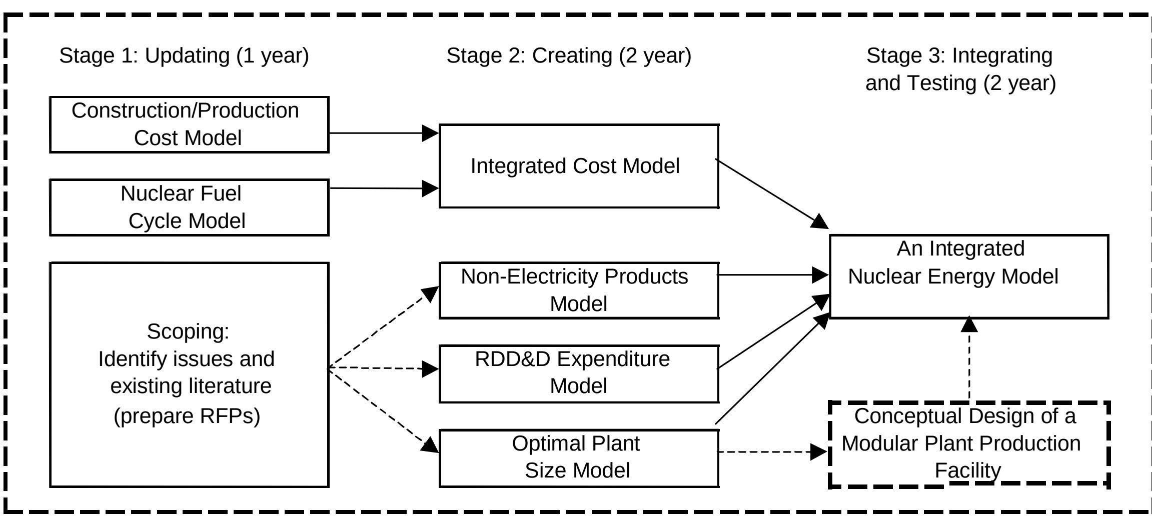

Figure 2. Creating an Integrated Nuclear Energy Model

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Appendix A

A Business Example of R&D Deployment Strategy

Appendix A

A Business Example of R&D Deployment Strategy

The Value Proposition Process described below has been used over a number of years to evaluate a broad range of projects and strategic company issues. It has proved highly effective in generating insights on those variables, which most influence a project ability to create value. This approach would provide GIF with a tool for assessing the progress of R&D projects initiated following the Generation IV Roadmap program.

A.1 THE VALUE PROPOSITION PROCESS

The overall process is shown in Figure A1, which also includes a summary of the activities and deliverables for each step of the process.

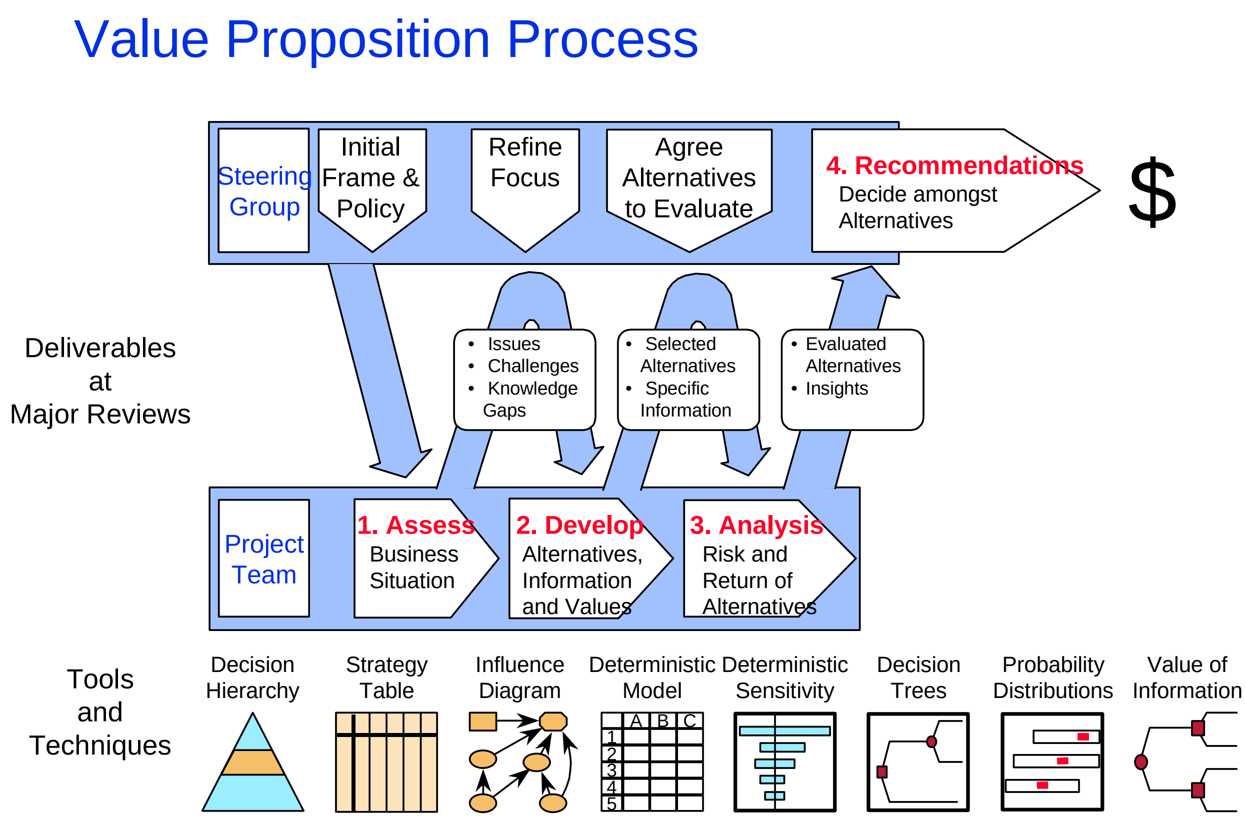

Figure A1. Schematic diagram of the overall Value Proposition Process.

The project participation is organized around four groups of people, as shown in Figure A2, including a steering committee, a working team, a project representation group and a resource group.

Key to achieving success is the formation of an appropriate steering group and working team. The members of the steering group are the customers for the project. The working team is responsible for providing information and analysis to individual projects; it will interact closely with an appropriate balance of staff, depending on the project being addressed, who will provide the necessary expertise to produce a high quality result.

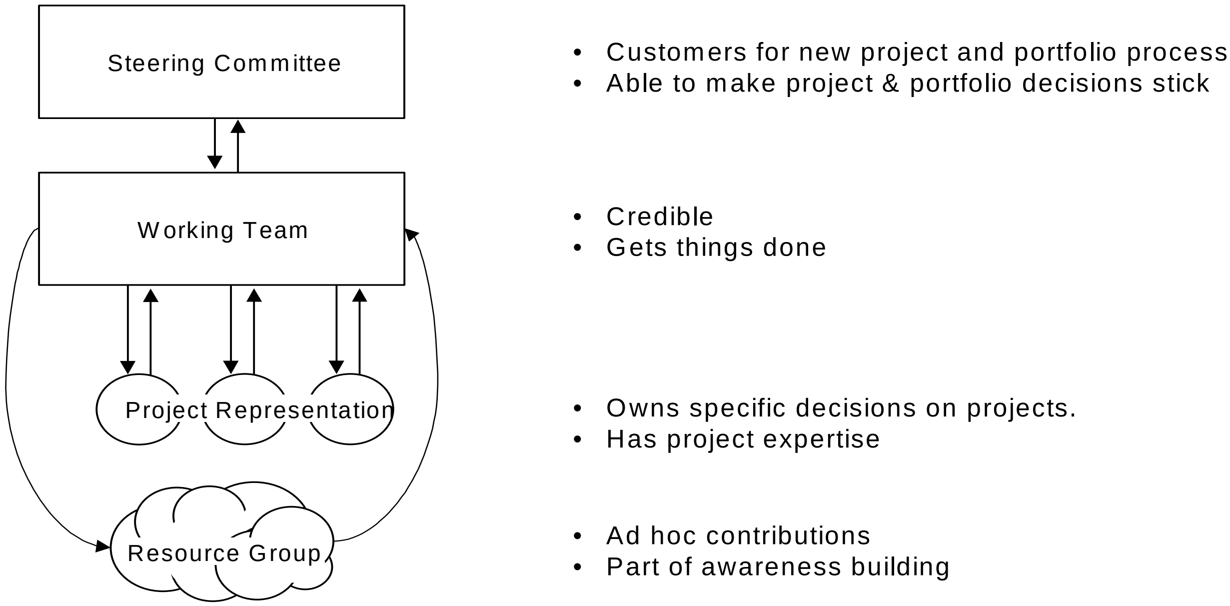

Figure A2. Project participation.

A list of typical outputs from an evaluation is given in Figure A3.

- Clear understanding of the problem being evaluated.
- A pictorial representation of the issues influencing value.
- A range of quantifiable alternative solutions.
- Common data set, agreed by Steering Committee and Working Team.
- A sensitivity analysis, helping project teams to focus their activities.
- Probability distributions, indication the overall level of risk and the likelihood of achieving a positive cash flow.
- Actionable conclusions, highlighting the best possibilities for creating value.

Figure A-3. Output from a typical valuation.

A.2 MAJOR ELEMENTS OF THE PROCESS

The process includes four major elements, which are discussed in detail below.

1. Initial Frame & Policy
   Assess Business Situation
   Refine and Focus
2. Develop Alternatives, Information and Values
   Agree Alternatives to Evaluate
3. Analysis
   Risk and Return of Alternatives
4. Recommendations
   Decide amongst Alternatives

A.2.1 Initial Frame and Policy

The steering group will formulate the initial frame and policy issues. The working team will have an opportunity to challenge these policy issues, bringing its knowledge to bear, but ultimately it is the responsibility of the steering group to decide policy.

The frame will include:

Purpose	—	What we intend to achieve
Perspective	—	The context in which the Project will be evaluated
Scope	—	The boundary of what is included and excluded

Assess Business Situation

In this step, the working team will put together a broad picture of what they know and what they must know about the project. The team will also consult experts and sources in and outside the company, with the aim of providing a credible factual basis for developing alternatives.

The key deliverable of this step will be a consensus view on the issues facing the Project. This includes clear statements of the strategic issues and challenges; a factual summary of the market, competitive, and regulatory situation; and a list of significant knowledge gaps that must be filled.

Refine and focus

This step is the first major interaction between steering group and the working team. The team will present its work on assessing the business situation to confirm understanding and promote discussion. The steering group will check that the appropriate frame has been created and will challenge the key deliverables, with a view to improving their quality and comprehensiveness.

A.2.2 Develop Alternatives, Information and Values

In this step, the working team will explore the entire range of alternatives the project could pursue. The focus will be on challenging the existing frame and assumptions about the business and think creatively.

The working team will include the ideas of all participants in the process and ensure that the alternatives developed are actionable. To accomplish the latter, alternatives will be described in terms of the key decisions needed for implementation. For example, they may include decisions about which products and services to develop, and what relationships to develop with customers, competitors and regulators.

In addition, the working team will generate specific new information to fill the knowledge gaps identified during the business assessment, using interviews with outside experts, benchmarking, and/or focus groups. The major deliverables of this step are 3 to 5 significantly different, creative, and actionable alternatives for the project.

Agree Alternatives to Evaluate

The aim of this step is to agree alternatives and develop buy-in at the steering group and subsequently throughout the related business groups.

A.2.3 Analysis

During this stage, the working team will collect the necessary information to enable financial evaluation of the chosen alternative. Each alternative will be assessed on a consistent unbiased basis, using the measure of net present value (NPV) of cash flow. In addition, insights relating to all major project variables will be developed and used to focus future project activities.

A.2.4 Recommendations

The steering group will fully discuss the evaluated alternatives, with the aim of deciding which direction the project should take. Decisions that require major capital, R&T, or other investments will be linked to a formal approval process. Decisions requiring a major change in direction or a major policy shift would need onward formal approval by the highest project management body, e.g., subset of GIF policy group, including representatives of the countries involved in the project.